Required Space Weather Reconnaissance in the Artemis Era

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Introduction

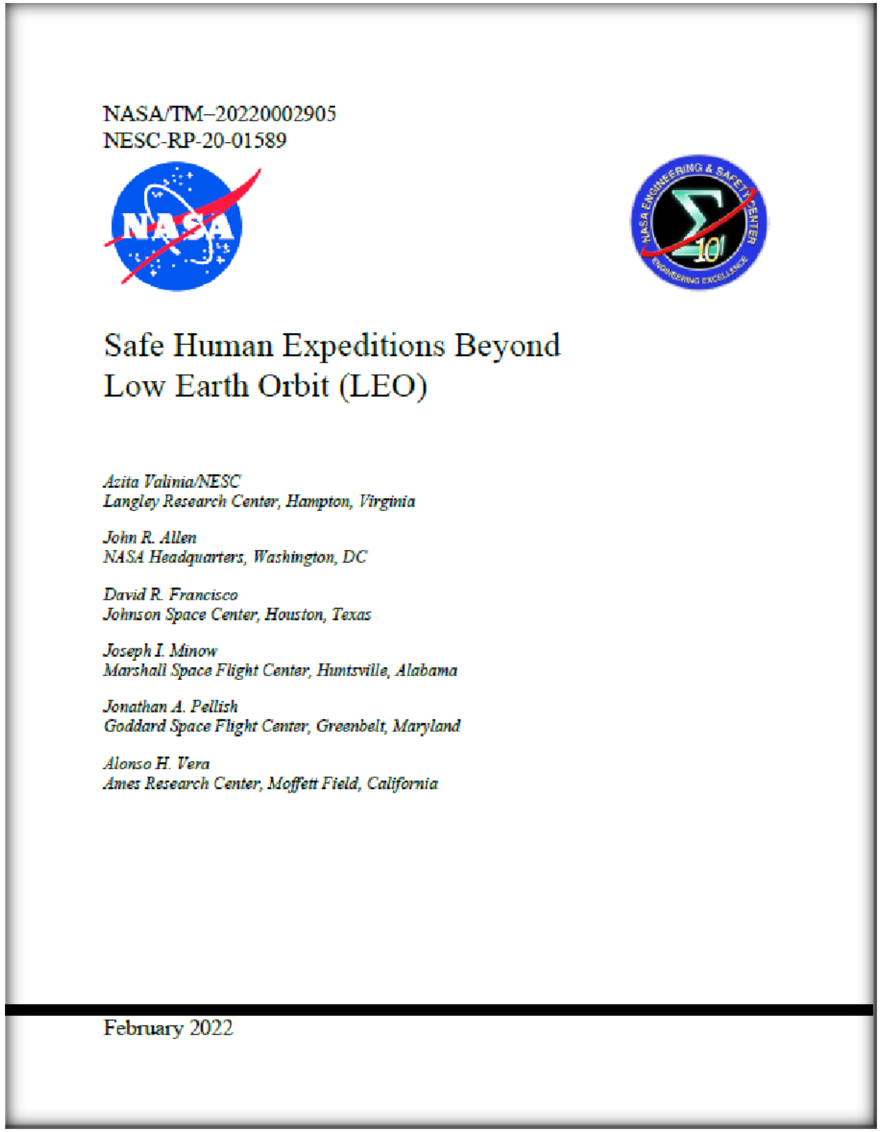
- NASA's Engineering & Safety Center (NESC) recently completed a study that included findings on space weather and space environments that impact human exploration in general and radiation monitoring and radiation shielding in particular:

  Safe Human Expeditions Beyond Low Earth Orbit
  Valinia, A., Allen, J., Francisco, D., Minow, J., Pellish, J., Vera, A.

  NASA/TM- 20220002905

  URL: https://ntrs.nasa.gov/citations/20220002905

- This paper summarizes selected radiation monitoring and shielding requirements from that report.


NASA/TM–20220002905
NESC-RP-20-01589

Safe Human Expeditions Beyond Low Earth Orbit (LEO)

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Hazards of Human Spaceflight

Focus of this paper

1 Space Radiation

Invisible to the human eye, radiation increases cancer risk, damages the central nervous system, and can alter cognitive function, reduce motor function and prompt behavioral changes.

2 Isolation and Confinement

Sleep loss, circadian desynchronization, and work overload may lead to performance reductions, adverse health outcomes, and compromised mission objectives.

3 Distance from Earth

Planning and self-sufficiency are essential keys to a successful mission. Communication delays, the possibility of equipment failures and medical emergencies are some situations the astronauts must be capable of confronting.

4 Gravity (or lack thereof)

Astronauts encounter a variance of gravity during missions. On Mars, astronauts would need to live and work in three-eighths of Earth's gravitational pull for up to two years.

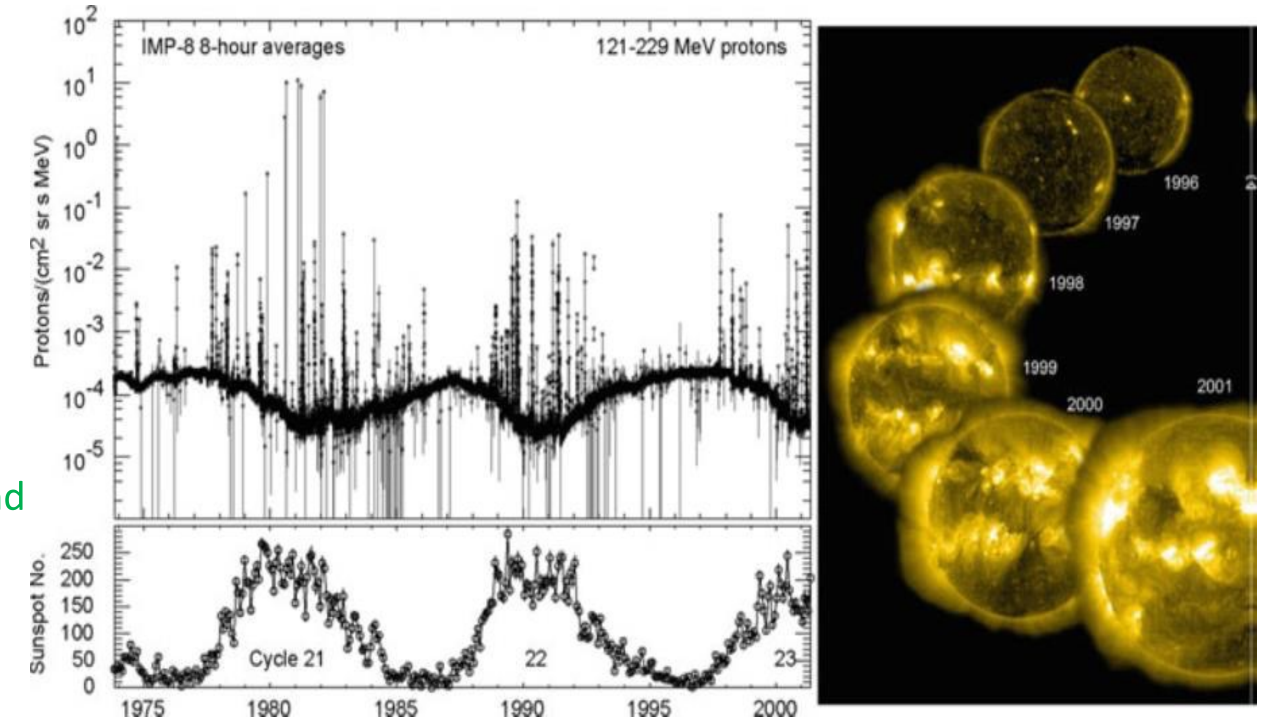
5 Hostile/Closed Environments

The ecosystem inside a vehicle plays a big role in everyday astronaut life. Important habitability factors include temperature, pressure, lighting, noise, and quantity of space. It's essential that astronauts stay healthy and happy in such an environment.

Current Knowledge of Radiation Environments

Earth's Radiation Belts

- Knowledge of long-term mean and statistical variations in the trapped radiation belt environments is sufficiently advanced to support design of crewed spacecraft that transit the belts on trajectories between LEO and the Moon and Mars, as long as the time spent in the belts is < 24 hours.
- Knowledge of long-term mean and statistical variations in the trapped radiation belt environments is sufficiently advanced to support design and operations of robotic missions that spend long periods of time in the radiation belts, such as the Gateway Power and Propulsion Element (PPE) and future uncrewed logistics vehicles using solar electric power to operate ion engines for gradual orbit raising through the belts.
- The ability to forecast the state of the radiation belts for specific short periods of time (i.e. on the order of several weeks) is currently limited due to the lack of nowcast data and predictive models.



(Top Left) Flux of 121–229 MeV protons for Cycles 21, 22, and 23
(Bottom Left) Monthly sunspot numbers provide phase in solar cycle
(Right) EUV images of Sun during rising phase of Cycle 23
[source: Reames 2021]

Galactic Cosmic Rays (GCR)

- GCR models are sufficiently advanced that they can be reliably (within %15) used to specify the flux of protons and heavy ions of importance to crew health and single event effects if the solar activity is known.
- The ability to predict future GCR environments is limited by the ability to predict future solar activity for periods of time beyond the minima in activity between 2 cycles.

Solar Particle Events

- Capability to nowcast (monitor) SEP events in LEO is sufficient to support crew warnings for onset of radiation events in time to implement radiation mitigation strategies.
- Capability to predict the onset of solar energetic particle events in advance is limited.

Model-calculated Mission (GCR) Radiation Exposures

NASA-STD-3001, Rev B., Vol. 1, Section 4.8.2: Career Space Permissible Exposure Limit for Space Flight Radiation

An individual astronaut's total career effective radiation dose (due to space flight radiation exposure) shall be less than 600 mSv. This limit is universal for all ages and sexes.

Shielding:
0, 20, 40 g/cm^2
spherical Al shield

GCR environment:
Solar min 2009
Solar max 2001

X/Y duration format:
X days in free space
Y days on surface

Effective dose* ≥600 mSv

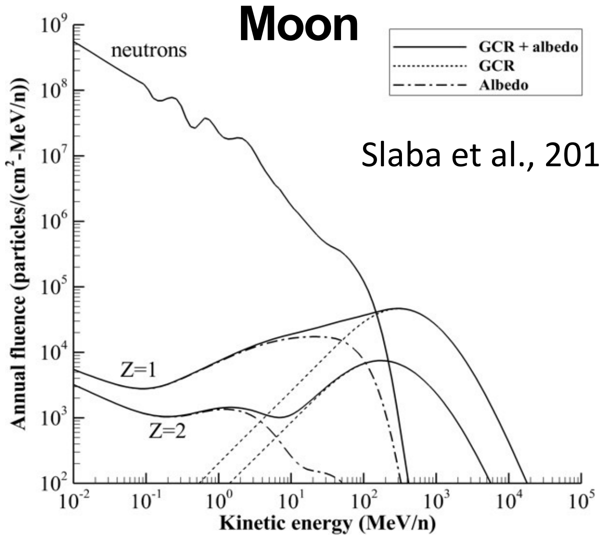
Effective dose is calculated using the approach described by Slaba et al. *Adv. Space Res.* **45**: 866-883; 2010.

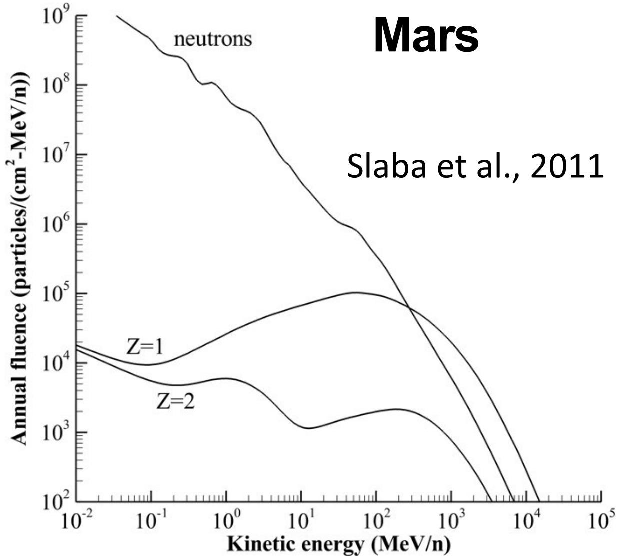
	Mission	Duration (days)	Dose (mGy)			Dose equivalent (mSv)			Effective dose (mSv)		
			0	20	40	0	20	40	0	20	40
solar maximum	Artemis II	10	1.5	2.1	2.5	10.2	6.9	5.9	6.3	5.1	5.3
solar maximum	Artemis III	30	4.6	6.4	7.6	30.5	20.7	17.6	19.0	15.4	15.8
solar maximum	Artemis III (surface)	23.5/6.5	4.2	5.8	6.9	27.7	18.7	16.0	17.4	14.1	14.4
solar maximum	Gateway – 6 month	183	28	39	46	186	126	108	116	94	96
solar maximum	Gateway – 12 month	365	56	78	92	372	252	215	232	188	192
solar maximum	Mars DRM	621/40	99	137	163	644	440	377	405	331	339
solar maximum	Mars DRM	840	128	178	213	855	580	494	533	432	442
solar minimum	Artemis II	10	4.6	5.2	5.6	28.5	15.0	12.2	14.6	10.9	10.7
solar minimum	Artemis III	30	13.8	15.5	16.7	85.5	44.9	36.5	43.8	32.8	32.1
solar minimum	Artemis III (surface)	23.5/6.5	12.6	14.0	15.0	77.1	40.5	33.0	39.8	29.9	29.2
solar minimum	Gateway – 6 month	183	84	95	102	522	274	223	267	200	196
solar minimum	Gateway – 12 month	365	168	189	203	1040	546	445	533	399	391
solar minimum	Mars DRM	621/40	295	332	356	1795	950	779	929	702	688
solar minimum	Mars DRM	840	386	434	466	2395	1256	1023	1228	918	899

Credit: Tony Slaba (NASA LaRC)

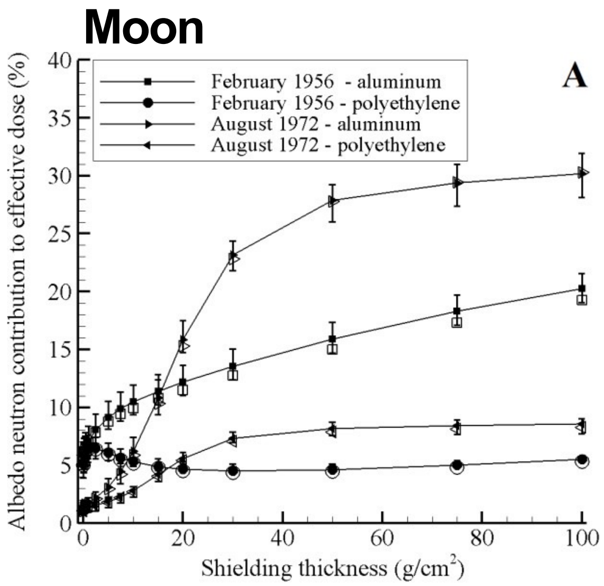
Lunar Neutron Environments

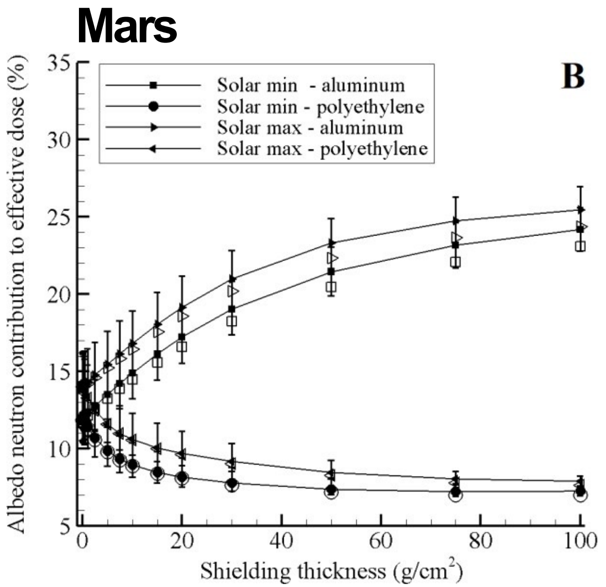
- Past efforts to measure lunar albedo neutrons have only extended to energies of 15 or 20 MeV
- In-situ measurements of the secondary neutron environment on the lunar surface extending beyond tens to hundreds of MeV to GeV energies are needed to support dose estimates for <u>long-term lunar exploration</u>
- A single mission is adequate to characterize the albedo environment since the goal is primarily to validate the nuclear interaction models used to simulate the production of neutrons from the GCR source and GCR flux varies slowly over time
- Lunar albedo neutron measurements are not required for the near-term missions to Gateway and the lunar surface since the current plan is to keep the mission durations sufficiently short such that GCRs and any albedo neutron contributions to crew dose are small compared with the NASA lifetime radiation exposure limit of 600mSv





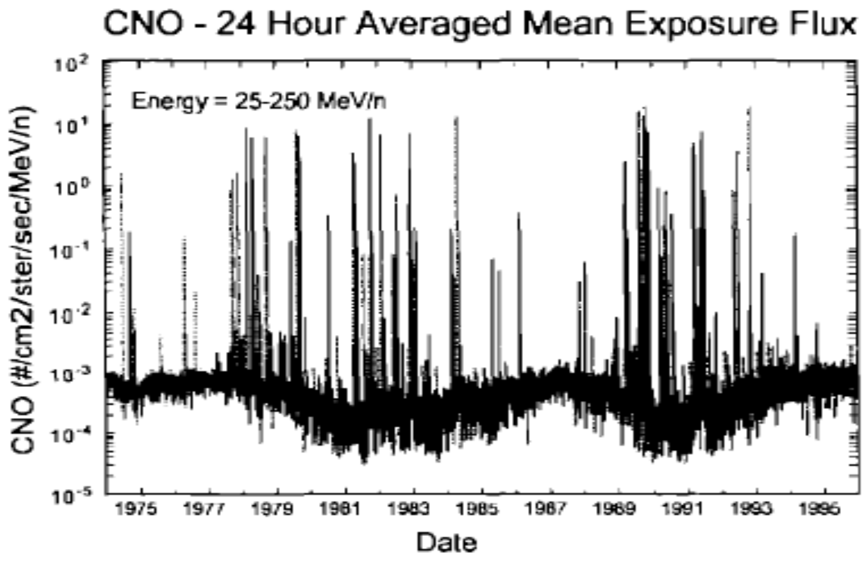
2009 Solar Minimum GCR Environments





Slaba et al., 2011

Radiation Monitoring Requirements

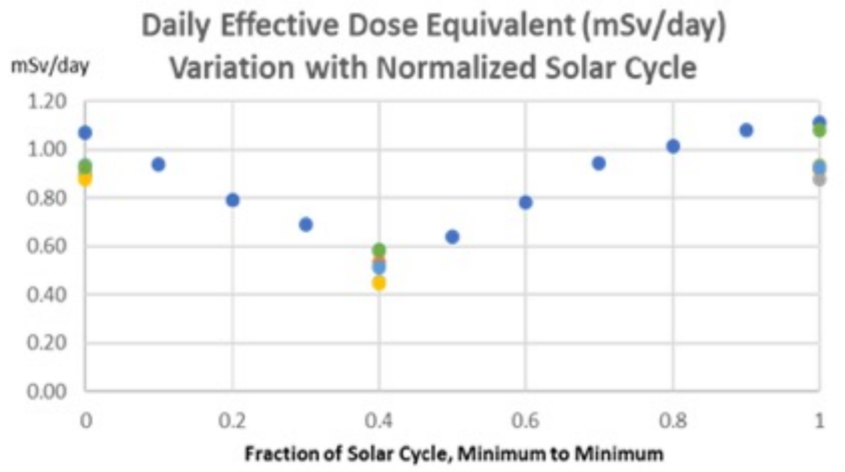


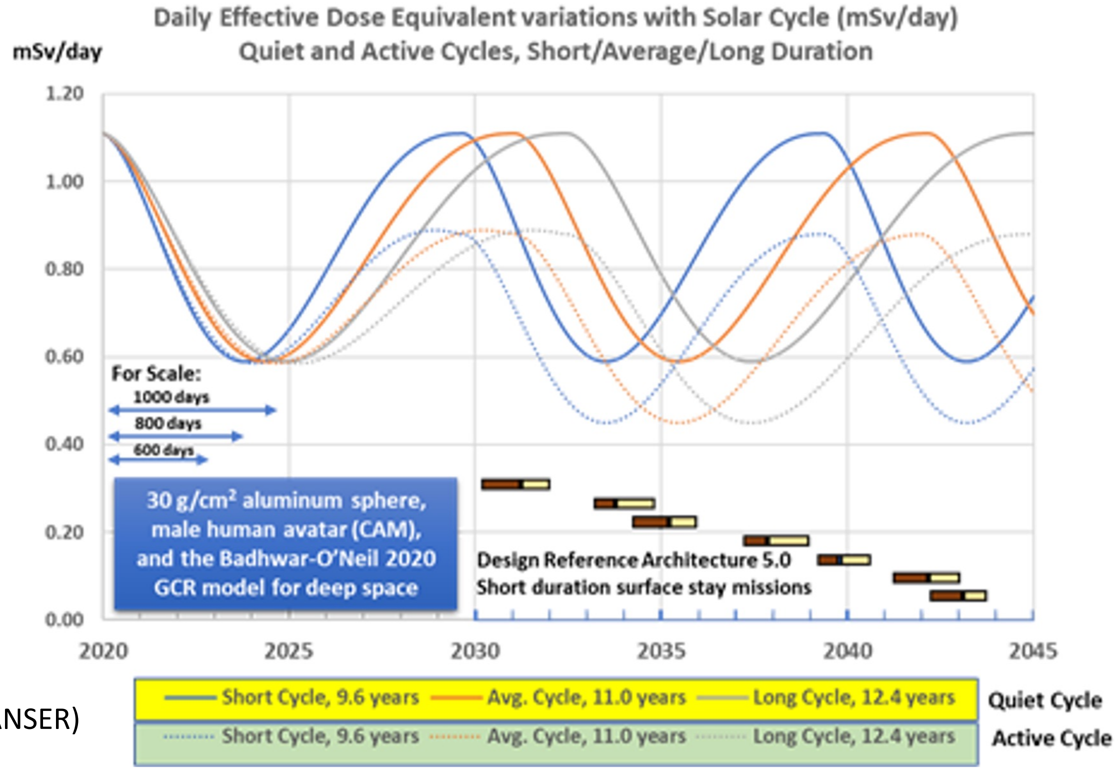
- ❖ Long-duration exploration missions into cislunar or interplanetary space will encounter solar particle event (SPE) and GCR radiation hazards
  - SPEs generated by coronal mass ejections are the greatest immediate threat to crew due to the rapid increase flux and the high ion flux levels that could be present during the events, which can last from hours to days
  - GCRs are a constantly present background of high-energy, low-flux particles that represent increased cancer risk and may cause CVD and CNS decrements on long-duration missions
- ❖ For SPEs, when adequate warning is given, the crew can take shelter for the duration of an event either by reconfiguring cargo in the vehicle or having a dedicated shelter
  - Radiation monitoring is required to alert crew to SPE onset, primary monitoring will be in-situ sensors located on crewed spacecraft (nowcast) with supplementary information for distributed sensors (forecasting)
  - For the return to the Moon, existing and planned scientific and operational ground- and space-based assets will provide sufficient warning of sporadic eruptions from the Sun. The planned crew shelters will provide adequate protection for the event duration with minimal impact to the completion of mission objectives.
  - For Mars missions, forecasting SPEs that will impact spacecraft and crew in interplanetary space becomes more challenging, and a key finding of this report is that new supporting infrastructure is required to give adequate warnings during crew transit and stay at Mars.
- ❖ **In-situ monitoring and infrastructure for forecasting SPE events are important because their episodic nature and rapid variations in intensity impact crew operations**
- ❖ **GCR intensity varies over solar cycle time scales and doesn't require the same short-term monitoring and forecasting used to mitigate SPE threats**

GCR Dose Variation with Solar Cycle

- **The energetic GCR ions are so penetrating that large shielding mass is required to mitigate GCR threats to crew health; GCR is a major radiation issue for long-term exploration of deep space**
- GCR flux varies slowly over solar cycle time scales (about a decade)
- The ability to forecast the shielding mass required to protect crew for upcoming missions as a function of phase in the solar cycle will complicate mission planning
- **Long-range Mars mission planning would benefit from efforts to improve the ability to forecast solar cycle length**
  - **Mars missions during solar maximum will substantially reduce crew dose**
  - **Increased shielding mass is required to keep crew radiation dose within program limits during solar minimum**
  - **Additional shielding mass reduces payload, impacting overall mission capability**

Effective Dose Equivalent (mSv/day)	
1965 Solar Minimum	0.89
1977 Solar Minimum	0.92
1987 Solar Minimum	0.88
1997 Solar Minimum	0.93
2010 Solar Minimum	0.93
2019 Approaching Minimum	1.08
1970 Solar Maximum	0.53
1982 Solar Maximum	0.45
1991 Solar Maximum	0.44
2001 Solar Maximum	0.51

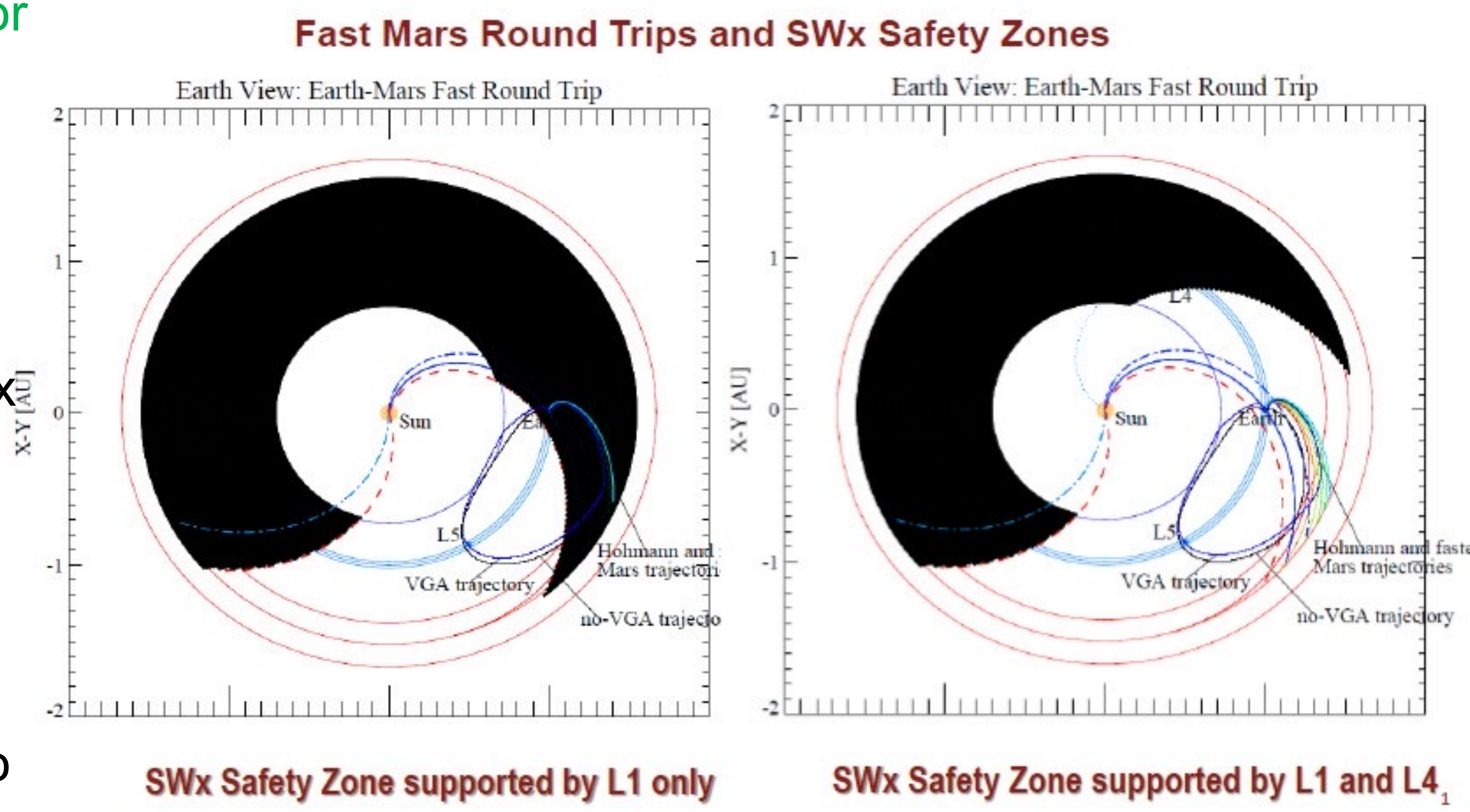




Credit: Ron Turner (ANSER)

Lagrange Point Space Weather Monitoring Platforms

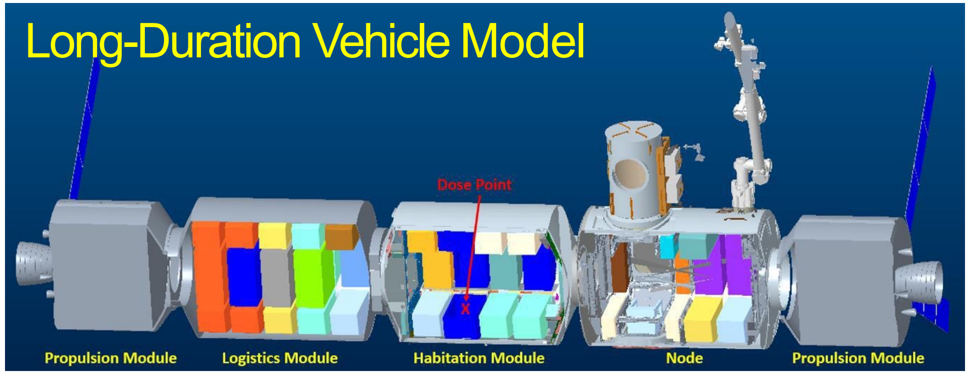
- In-situ monitoring and assets at Sun-Earth L1 provide adequate coverage for near term missions to the Moon
- Additional space weather monitoring assets (i.e., solar coronagraph and particle detector suites) at Sun-Earth Lagrange point L4 and L5 provide additional opportunities to monitor SWx for lunar missions and short-term missions to Mars
- Sun-Mars L1 and L4/L5 can enable sufficient early warnings for Mars missions during transit and stay.
- The Sun-Mars L4/L5 assets would also provide a communications relay solution for when the Earth line of sight to Mars is behind or close to the Sun, leading to a 2-week blackout period every 2 years.

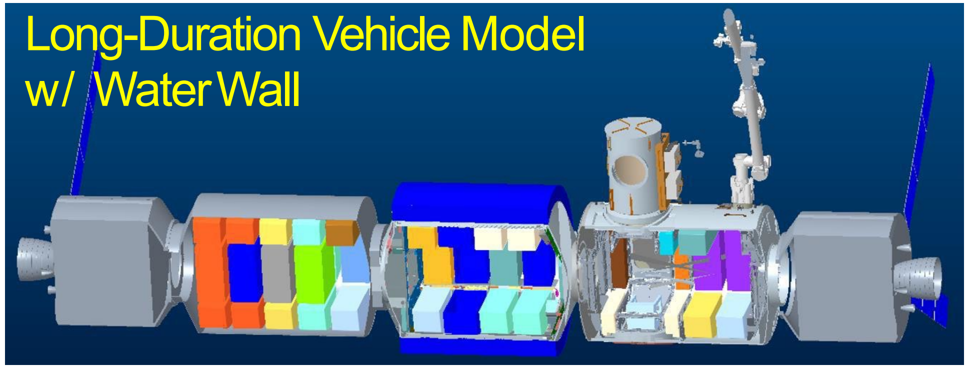


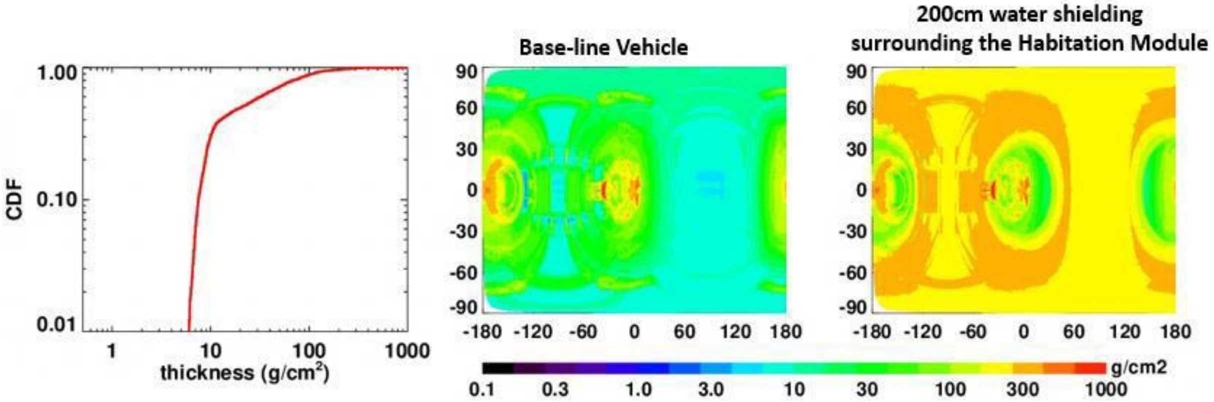
Credit: Noble Hatten (APL)

Passive GCR Shielding for a Mars Mission

- Radiation shielding as a function of a water-wall thickness evaluated for GCR environment
- Radiation shielding design needs to be part of the early design process of any vehicle or habitat, to maximize the shielding provided by the required vehicle mass as opposed to the incorporation of additional parasitic shielding mass
- Baseline (no supplemental water-wall shielding):
  - Solar minimum 1.08 mSV/day
  - Solar maximum 0.55 mSV/day
- Demonstrates the advantage of traveling to/from Mars at solar maximum assuming ability to adequately shield SPEs with passive shielding







Credit: Ryan Norman (NASA LaRC)

Passive GCR Shielding for a Solar Minimum Mars Mission

- Large water-shielding thickness on the order of 1000 cm may be needed to reduce the exposure of solar minimum GCR environment to the exposure level for solar maximum GCR

- The uncertainty in transport codes used to study the shielding efficacy is largely unquantified at material thicknesses greater than ~100 g/cm2, additional work needs to be done to quantify the uncertainty in transport codes for these large shielding values

- Table shows number of launches required to deliver water mass to initial LEO orbit
  - Examples provided for three launch vehicle classes:
    small, medium, and large
  - Arbitrary color scale to emphasize when water mass is
    Less than 20% of payload mass
    20% to 100% of payload mass
    1 to 2 launches
    More than 2 launches

Water-wall Thickness (cm)	Dose Equivalent (mSv/day)	Reduction in Dose Equivalent (%)	Water-Wall Mass (kg)	Number of Launches		
				10,000 kg per launch[a]	50,000 kg per launch[b]	100,000 kg per launch[c]
0	1.08	0	0.0	**0**	**0**	**0**
20	1.06	1.9	1,900	**0.19**	**0.038**	**0.019**
50	1.10	-1.9	4,700	**0.47**	**0.094**	**0.047**
100	1.10	-1.9	9,300	**0.93**	**0.19**	**0.093**
200	0.96	10.7	18,700	**1.87**	**0.37**	**0.19**
300	0.83	23.6	28,000	**2.80**	**0.56**	**0.28**
400	0.72	33.7	37,300	**3.73**	**0.75**	**0.37**
500	0.65	40.0	46,700	**4.67**	**0.93**	**0.47**
1000	0.55	49.0	93,000	**9.30**	**1.86**	**0.93**

Launch vehicle payload to LEO classification (within about 2x):
[a]Atlas V, Falcon 9, Antares, Delta IV
[b]Falcon Heavy, New Glenn
[c]Saturn V, SLS, Starship

Launches < 0.20 0.2 < L < 1.0 1.0 < L < 2.0 L > 2.0

Key Take-Aways

National Aeronautics and
Space Administration

- In the Artemis Era, astronauts will be exposed to radiation hazards from Solar Particle Events (SPE) as well as Galactic Cosmic Radiation (GCR) for long durations.
- Model-based calculations show that the total effective dose during extended lunar expeditions can be below the astronaut lifetime limit with current shielding technologies for vehicle and habitats, and when sufficient advanced warning of sporadic eruptions from the Sun is provided so that sheltering measures can be put into place.
- For long-duration Mars missions, the total GCR effective dose will exceed lifetime crew limits. Advanced mitigation strategies to keep the crew safe from cumulative hazards of radiation are needed.
- For crewed missions to Mars (when timely communication with Earth is not feasible), it will be necessary to monitor and forecast SPE on location instead of relying on operational instructions based on forecasts generated and transmitted from Earth. This will require monitoring assets and forecasting capabilities in the vicinity of Mars.